GENERAL APPROACH TO CHROMATIC DISPERSION ANALYSIS OF MICROWAVE OPTICAL LINK ARCHITECTURES

A.Hilt♦°#, G.MAURY°, B.CABON°, A.VILCOT°, L.GIACOTTO°

♦ *BME-MHT, Technical University of Budapest, Department of Microwave Telecommunications*
H-1111 Goldmann György tér 3. V2.ép. VI.em., Budapest, HUNGARY
fax.: (+36 1) 463 32 89, tel.: (+36 1) 463 41 42, e-mail : hilt@mht.bme.hu

° *LEMO-ENSERG-INPG, Institut National Polytechnique de Grenoble*
23 Rue des Martyrs, BP 257, F-38016 Grenoble, Cedex 1, FRANCE
tel.: (+33) 04 76 85 60 15, fax: (+33) 04 76 85 60 80, e-mail : maury @ enserg.fr

TKI Rt, Innovation Company for Telecommunications,
H-1142 Ungvár utca 64-66, Budapest, HUNGARY
tel.: (+36 1) 252 70 01, fax.: (+36 1) 251 98 78, hilt@ tki.hu

Introduction

Fiber-optical transmission of microwave (MW) and millimeter-wave (MMW) signals in the λ=1.55 µm wavelength window has become an intensive research area of MW photonics recently [1]. A main field of potential applications is the optical transmission and wireless distribution of broadband data in future picocellular access systems [2-5]. A seemingly simple solution utilizes very high-speed external modulators or direct modulated lasers and ultra-fast optical receivers for MW/MMW signal distribution over the optical network. Then in the last few hundred meters the optically fed base station is connected to the subscribers by MW or MMW radio channels. The increasing demand for higher and higher carrier frequencies in the radio channels requires even MMW optical links. Amplification is performed in the optical path by Erbium-doped fiber amplifiers (EDFA). However, chromatic dispersion of standard singlemode fibers (SMF) at λ=1.55 µm leads to a drastic penalty in detected signal strength [4-7].

MW/MMW optical link models

Usual MW fiber-optical link models predict the overall link performance (link gain, noise figure) based on an incoherent model, where the optical signal is intensity modulated (IM) by a MW or MMW envelope [8]. The modulated optical power is injected into the fiber, where losses are taken into account to determine the received optical power. Since this model is based on the intensity instead of the optical field, such phenomena as chirp, chromatic or polarization mode dispersion cannot be handled. The validity of incoherent link models at λ=1.55 µm is therefore limited to few hundred meters and to rather low IM frequencies (below 3 GHz). The output optical spectra of either direct modulated lasers or external optical intensity modulators contain satellite peaks around the optical carrier [3, 4, 9]. At very high IM frequencies falling into the MMW range, these satellite peaks have a frequency separation in the orders of several 10 GHz, so they propagate with different speed in the optical fiber due to chromatic dispersion. The typical dispersion value of standard SMFs is about 17 ps/nm/km. As a result, depending on the fiber length and the IM frequency, a complete rejection of the modulation content can happen. Until now only analytical models explained the effect of chromatic dispersion [6, 10], but a general simulation method has not been reported. The main difficulty of analytical models is in the large number of different link architectures. For each specific problem a new analytical model should be derived.

Coherent model of the optical link

Based on a coherent model we developed a general simulation tool for analyzing different fiber-optical link architectures [11]. This model predicts link performance numerically by using building blocks of direct or external modulation, dispersive fiber and coherent photodetection at the receiver side. The optical field at the single-frequency modulated LD output is written as :

$$E(t) = E_0\sqrt{1+m\cos(\omega_{RF}t)}\,e^{j\left\{\omega_{opt}t+\beta\cos[\omega_{RF}t+\theta]+\phi(t)\right\}}, \qquad (1.)$$

where β is the usual frequency modulation (FM) index, $\phi(t)$ is the phase noise term and θ is the phase delay between AM and FM. Its typical value is between 0 and $-\pi/2$. Usually Eq.1 is simplified as [9] :

$$E(t) = E_0\sqrt{1+m\cos(\omega_{RF}t)}\, e^{j\{\omega_{opt}t+\beta\sin[\omega_{RF}t+\theta_a(\omega_{RF},I_0)]\}}\,, \tag{2.}$$

where θ_a is the phase lag in addition to $\pi/2$. As indicated, θ_a is frequency and optical power dependent. In the case of external modulation by a dual-electrode interferometer the optical field is :

$$E(t) = \frac{E_o}{2}\left[\cos(\omega_o t+\gamma_1\pi+\alpha_1\pi\cos\omega_{RF1}t)+\cos(\omega_o t+\gamma_2\pi+\alpha_2\pi\cos(\omega_{RF2}t+\theta_{RF}))\right], \tag{3.}$$

where Θ_{RF} represents the phase difference between the driving RF signals of the two electrodes. γ_i and α_i are the normalized DC and RF voltages driving the modulator arms, respectively. A special case of Eq.3 is given by γ_1=-γ_2=γ/2, α_1=-α_2=α/2 and Θ_{RF}=0. These values result in the important case of the balanced push-pull Mach-Zehnder modulator (MZM) :

$$E(t) = E_o\cos(\omega_o t)\cos\left[\gamma\frac{\pi}{2}+\alpha\frac{\pi}{2}\cos(\omega_{RF}t)\right]\ . \tag{4.}$$

For $\gamma_2 = \alpha_2 = \Theta_{RF} = 0$, $\gamma_1 \neq 0$ and $\alpha_1 \neq 0$ we arrive to the single electrode MZM :

$$E(t) = \frac{E_o}{2}\left[\cos\omega_o t+\cos[\omega_o t+\gamma\pi+\alpha\pi\cos(\omega_{RF}t)]\right]\ . \tag{5.}$$

In general ω_{RF1} = ω_{RF2}, since only one RF signal modulates the MZM. In some cases however, optical-microwave mixing is required [5, 9], therefore in a general model ω_{RFi} may be different. The optical field in frequency domain is expressed by Fourier transform of the field given in time domain in Eq.1-5. Finally, the output optical field at the fiber end is calculated as :

$$E_{opt,out}(\omega_{opt}) = E_{opt,in}(\omega_{opt})H_{opt}(\omega_{opt}) = E_{opt,in}(\omega_{opt})A(L)e^{-j\beta(\omega_{opt})L}\,, \tag{6.}$$

where L is the fiber length and $\beta(\omega)$ is the propagation factor. Based on Eq.1-6 and using FFT we can calculate the output optical field. Due to quadratic photodetection, the current of an ideal PD is proportional to the optical intensity :

$$i_{PD}(t) \propto 2\left\langle E^2_{opt,out}(t)\right\rangle = E_{opt,out}(t)E^*_{opt,out}(t)\ . \tag{7.}$$

The general model is shown in Fig.1. As indicated, also the non-ideal frequency response of the modulator and of the photodetector can be taken into account.

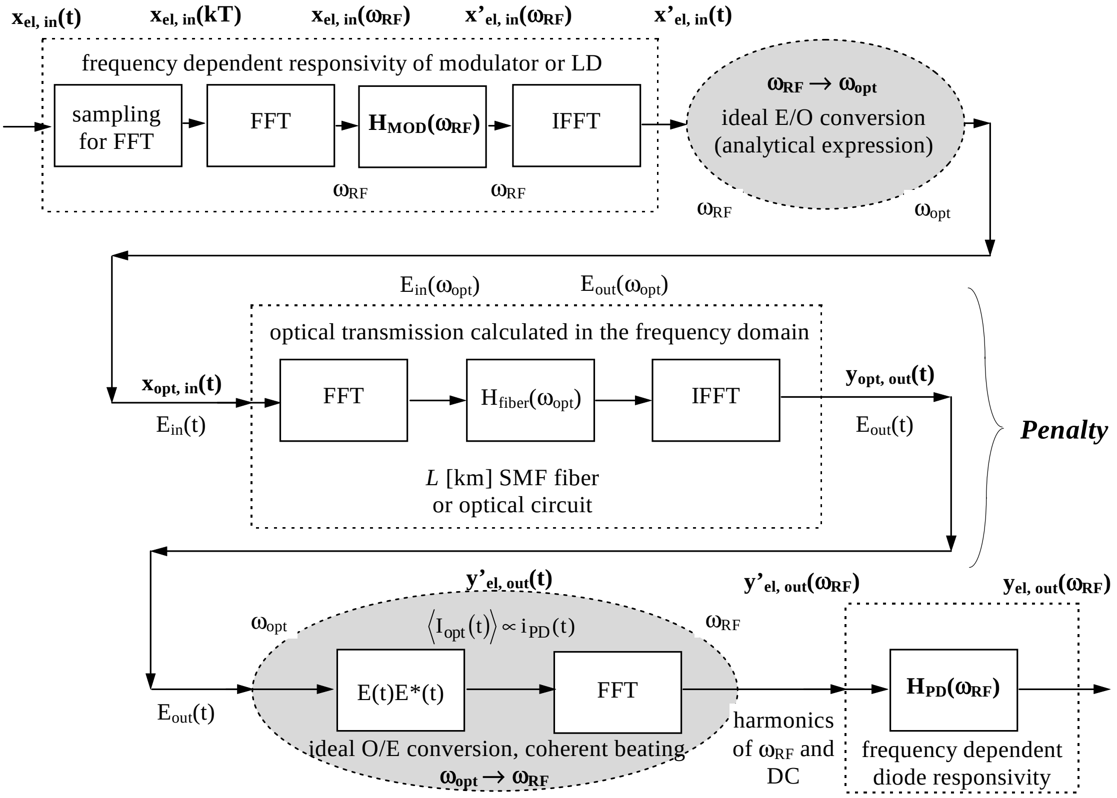

Figure 1. Coherent model of polarization maintaining fiber-optical link as used in our computer simulations

Simulation results

Fig.2 shows the detected power of the optically transmitted signal using classical externally modulated optical link. The effect of chromatic dispersion is clearly seen resulting in periodic rejections as a function of fiber length L and modulation frequency f_{RF}.

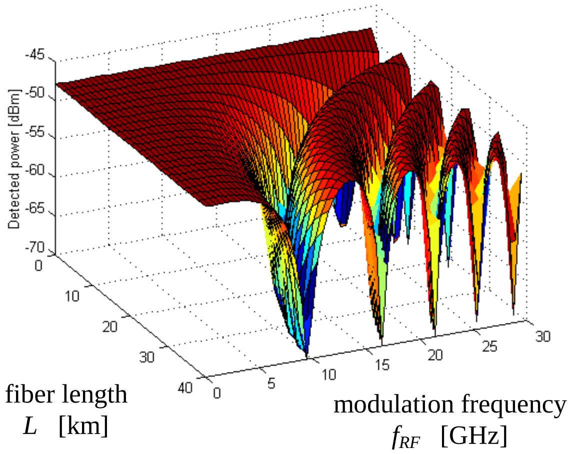

Figure 2. Detected power level of MW signal transmitted optically in dispersive fiber. (Linear modulator bias of γ=0.5, α=0.25, D=17ps/km/nm, R_{PD}=0.35 A/W)

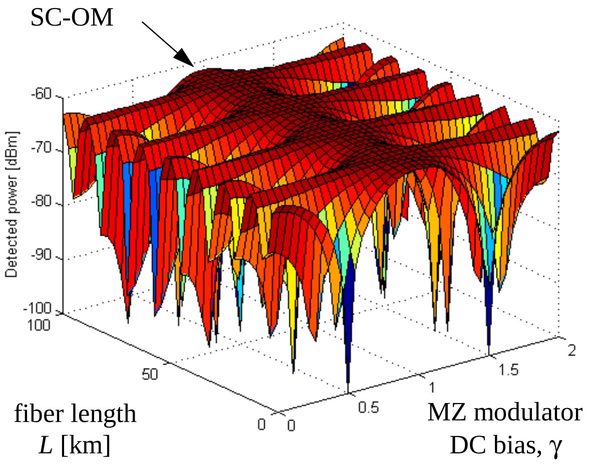

Figure 3. Detected 2nd harmonic level after transmission in dispersive fiber, (f_{RF} =12 GHz, α=0.25, D=17ps/km/nm, R_{PD}=0.35 A/W).

To avoid chromatic dispersion, several proposals have been reported. Fig.3 plots suppressed carrier optical modulation (SC-OM) achieved by a normalized modulator bias of $\gamma=V_{\mathrm{DC}}/V_{\pi}=1$ [6]. At this special bias 2nd harmonic of the 12 GHz modulation signal is generated. Advantageously, SC-OM is unaffected by chromatic dispersion. Single sideband optical modulation (SSB-OM) offers a further perspective solution of dispersion-free optical transmission of MW/MMW signals at 1.55 µm. One SSB-OM method filters out optically one of the sidebands [12]. Another solution uses dual-electrode optical modulator [10]. The MW modulation signal is splitted into two, and a θ_{RF} = 90° phase difference is introduced between the drive signals. As presented in Fig.4 at γ=0.5 lower sideband optical modulation (LSB-OM) while at γ =1.5 upper sideband optical modulation (USB-OM) is generated. Fig.5 shows the detected first harmonic power level as a function of modulation frequency and fiber length, respectively. The modulator bias is γ=0.5 and θ_{RF} =90° to achieve ideal SSB-OM. It is worth to compare Fig.5 to Fig.2, the detected level has somewhat decreased but rejections are avoided.

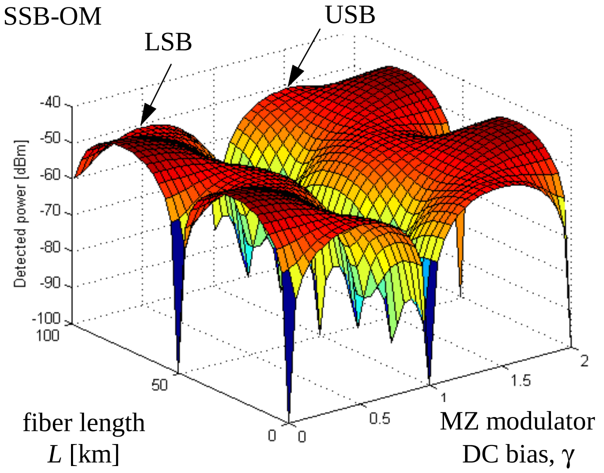

Figure 4. Detected power level of first harmonic vs. normalized modulator bias γ and fiber length L (f_{RF} =12 GHz, α=0.25, Θ_{RF}=90°, D=17ps/km/nm).

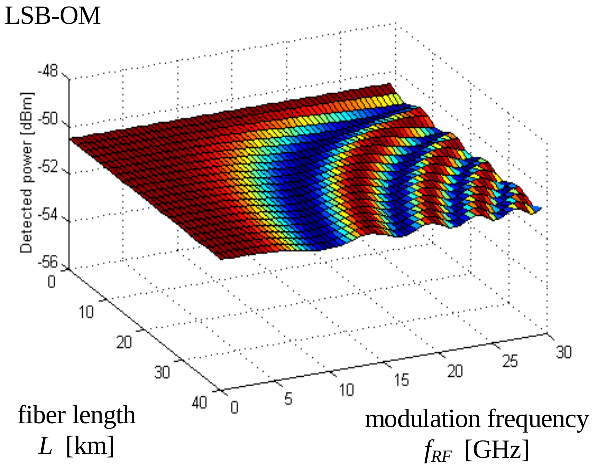

Figure 5. Detected level of LSB-OM first harmonic (γ=0.5, α=0.25, Θ_{RF} =90°, D=17ps/km/nm, R_{PD}=0.35 A/W).

Finally, we demonstrate a remote upconversion method based on an all-optical device inserted in the MW optical link. A laser diode is directly modulated by two MW frequencies and an unbalanced Mach-Zehnder interferometer (UMZI) performs optical FM/AM conversion. Now the transfer function of the fiber is simply multiplied by the transfer function of the UMZI. This way optical-MW upconversion is obtained due to quadratic photodetection [13, 14]. Dispersion sensitivity of this configuration is also investigated by simulations supposing D=17 ps/km/nm fiber dispersion at λ=1.55µm. Fig.6 and Fig.7 show first and 2nd harmonic power levels after quadratic photodetection.

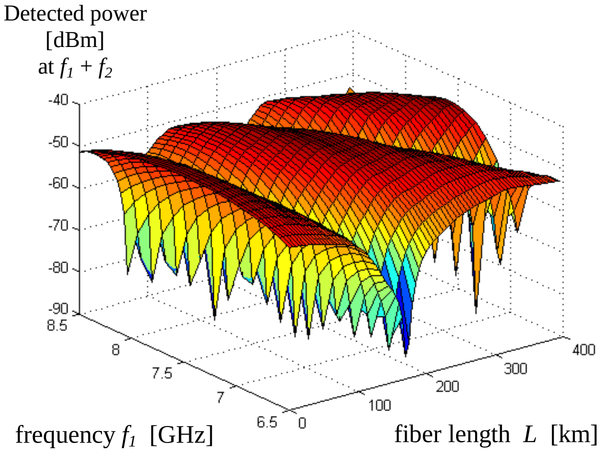

Figure 6. Detected upconverted level at f_{RF1}+ f_{RF2} vs. dispersive fiber length L and f_{RF1}, f_{RF2}=4.5GHz.

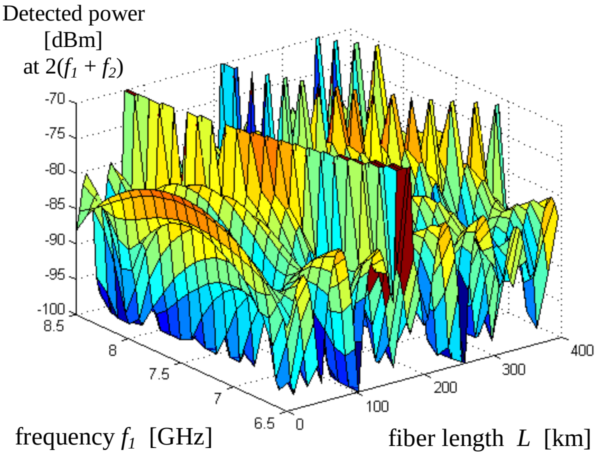

Figure 7. Detected level of the second harmonic of the upconverted signal vs. dispersive fiber length L and f_{RF1}

Acknowledgements

The authors wish to acknowledge the Commission of the European Union and the Hungarian Scientific Research Fund for their continuous support to their research work (under the projects of KIT, FRANS and OTKA No. T017295, F024113, T030148, T026557, T019857).

References :

[1] B.A.Galwas : "Photonic Technology for Microwave Engineering", *Proc. of the International Conference on Microwaves and Radar, MIKON'98, Vol.4, pp.117-134*, Kraków, Poland, May 1998.

[2] T.Marozsák, T.Berceli, G.Járó, A.Zólomy, A.Hilt, S.Mihály, E.Udvary, Z.Varga : "A New Optical Distribution Approach for Millimeter Wave Radio", *MWP'98 Digest, pp.63-66*, Princeton, New Jersey, USA, October, 1998.

[3] A.Hilt, T.Marozsák, G.Maury, T.Berceli, B.Cabon, A.Vilcot : "Radio-Node Upconversion in Millimeter-Wave Fiber-Radio Distribution Systems", *Proc. of MIKON'98, Vol.1, pp.176-180,* Kraków, Poland, 20-22 May 1998.

[4] A.Hilt, A.Vilcot, T.Berceli, T.Marozsák, B.Cabon : "New Carrier Generation Approach for Fiber-Radio Systems to Overcome Chromatic Dispersion Problems", *IEEE MTT-S Digest, pp.1525-1528,* Baltimore, USA, June 1998.

[5] A.Hilt : "Transmission et traitement optiques des signaux dans les systèmes de télécommunications hertziens", *Ph.D. thsesis, Institut National Polytechnique de Grenoble,* Grenoble, France, 17. May 1999.

[6] H.Schmuck : "Comparison of optical millimetre-wave system concepts with regard to chromatic dispersion", *Electronics Letters, Vol.31, No.21, pp.1848-1849,* 12th October 1995.

[7] T.Marozsák, S.Mihály, T.Berceli : "Single Mode Fiber Dispersion in Microwave Optical Systems Using Direct Detection", *Proc. of the 1st Electronic Circuits and Systems Conference, ECS'97,* Slovak Republic, September 1997.

[8] C.H.Cox III., G.E.Betts, L.M.Johnson : "An Analytic and Experimental Comparison of Direct and External Modulation in Analog Fiber-Optic Links", *MTT, Vol.38, No.5, pp.501-509,* May 1990.

[9] G.Maury : "Mélange de signaux microondes par voie optique", *thèse de doctorat, LEMO, ENSERG, INPG,* Grenoble, France, Novembre 1998.

[10] G.H.Smith, D.Novak : "Broad-Band Millimeter-Wave (38GHz) Fiber-Wireless Transmission System Using Electrical and Optical SSB Modulation to Overcome Dispersion Effects", *IEEE PTL, Vol.10, No.1, pp.141-143,* January 1998.

[11] A.Hilt, G.Maury, A.Vilcot, B.Cabon : "Numerical Model of Chromatic Dispersion Effects in Analogue IM/DD Optical Links", *Proc. of the 2nd International Summer School on Interactions between Microwaves and Optics, OMW'99,* Autrans, France, July 1999.

[12] J.Park, W.V.Sorin, K.Y.Lau : "Elimination of the Fibre Chromatic Dispersion Penalty on 1550 nm Millimetre-Wave Optical Transmission", *Electronics Letters, Vol.33, No.6, pp.512-513,* 13th March 1997.

[13] G.Maury, A.Hilt, B.Cabon, V.Girod, L.Degoud : "Remote Upconversion in Microwave Fiber-Optic Links Employing an Unbalanced Mach-Zehnder Interferometer", *Proc. of the SPIE's 44th Annual Meeting, Terahertz and Gigahertz Photonics Confrerence, paper 3795-71,* Denver, Colorado, USA, 18-23 July 1999.

[14] T.Berceli, A.Hilt, G.Járó, G.Maury : "Optical Processing and Transmission of Subcarrier Multiplexed Microwave Signals", *accepted for presentation at the 29th EuMC Workshop,* München, Germany, October 1999.